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From link dynamics to path lifetime and packet-length optimization in MANETs

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Abstract We present an analytical framework and statistical models to accurately characterize the lifetime of a wireless link and multi-hop paths in mobile ad hoc networks (MANET). We show that the lifetimes of links and paths can be computed through a two-state Markov model. We also show that the analytical solution follows closely the results obtained through discrete-event simulations for two mobility models, namely, random direction and random waypoint mobility models. We apply these models to study practical implications of link lifetime on routing protocols. First, we compute optimal packet lengths as a function of mobility, and show that significant throughput improvements can be attained by adapting packet lengths to the mobility of nodes in a MANET. Second, we show how the caching strategy of on-demand routing protocols can benefit from considering the link lifetimes in a MANET. Finally,we summarize all the analytical results into a comprehensive performance analysis on throughput, delay and storage.

Keywords Link dynamics · Analytical mobility modeling · Path lifetime · Markov model · Optimal information segmentation

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1 Introduction

The communication protocols of mobile ad hoc networks (MANET) must cope with frequent changes in topology due to node mobility and the characteristics of radio channels. From the standpoint of medium access control (MAC) and routing, node mobility and changes in the state of radio channels translate into changes in the state of the wireless links established among nodes, where typically a wireless link is assumed to exist when two nodes are able to decode each other's transmissions.

The motivation for this paper is that, while the behavior of wireless links is critical to the performance of MAC and routing protocols operating in a MANET, no analytical model exists today that accurately characterizes the lifetime of wireless links, and the paths they form from sources to destinations, as a function of node mobility. As a result, the performance of MAC and routing protocols in MANETs have been analyzed through simulations, and analytical modeling of channel access and routing protocols for MANETs have not accounted for the temporal nature of MANET links and paths. For example, the few analytical models that have been developed for channel access protocols operating in multihop ad hoc networks have either assumed static topologies (e.g., [1]) or focused on the immediate neighborhood of a node, such that nodes remain neighbors for the duration of their exchanges (e.g., [2]). Similarly, most studies of routing-protocol performance have relied exclusively on simulations, or had to use limited models of link availability (e.g., [3]) to address the dynamics of paths impacting routing protocols (e.g., [4]).

This paper provides the most accurate analytical model of link and path behavior in MANETs to date, and characterizes the behavior of links and paths as a function of node mobility. The importance of this model is twofold. First, it enables the investigation of many questions regarding fundamental tradeoffs in throughput, delay and storage requirements in MANETs, as well as the relationship between many cross-layer-design choices (e.g., information packet length) and network dynamics (e.g., how long links last in a MANET). Second, it enables the development of new analytical models for channel access, clustering and routing schemes by allowing such models to use link lifetime expressions that are accurate with respect to simulations based on widely used mobility models.

Recently, Samar and Wicker [5, 6] pioneered the analytical evaluation of link dynamics, and provided new insight on the importance of an analytical formulation of link dynamics in the optimization of the protocol design. However, Samar and Wicker assumed that communicating nodes maintain constant speed and direction in order to evaluate the distribution of link lifetime. This simplification overlooks the case in which either one of the communicating nodes changes its speed or direction while the nodes are in transmission range of each other. As a result, the results predicted by Samar and Wicker's model could deviate from reality greatly, being overly conservative and underestimating the distribution of link lifetime [5, 6], especially when the ratio R/v between the radius of the communication range R to the node speed v becomes large, such that nodes are likely to change their velocity and direction during an exchange.

The contribution of this paper is to provide a two-state Markov model that better describes the mobility patterns of communicating nodes. Section 2 describes the network and mobility models used to characterize link and path behavior. Section 3 describes the proposed analytical framework and presents our results on link lifetime, and Sect. 4 extends these results to path dynamics. Our approach is based on a two-state Markovian model that reflects the movements of nodes inside the circle of transmission range and builds an analytical framework to accurately evaluate the distribution of link lifetime.

Our model subsumes the model of Samar and Wicker [5, 6] as a special case, and provides a more accurate characterization of the statistics of link lifetime. Section 5 illustrates the accuracy of our analytical model by comparing the analytical results against simulations based on the random direction mobility model (RDMM) and the random waypoint mobility (RWP) model.

Sections 6 and 7 illustrate how our model can be applied to practical problems in MANETs. Section 6 applies our analytical framework to optimal segmentation (information packet length) of information streams. Our results reveal that packet lengths should be designed to be linearly proportional to the ratio R/v, and show that the optimal packet length for a given K-hop path should be designed to be $R/(vK)$. Section 7 discusses improving packet caching policies in on-demand routing protocols by taking advantage of the characterization of link and path lifetimes. A comprehensive coverage of throughput, delay and storage requirement is then followed in Sect. 8. Part of the material in this paper was presented in [7], for a particular mobility model (RDMM) and restricted mobility of nodes. This paper considers a more general random mobility model, extensions to path dynamics, and unrestricted node mobility.

2 System model

Consistent with several prior analytical models of MANETs [8–10], we consider a square network of size $L \times L$ in which n nodes are initially randomly deployed. The movement of each node is unrestricted, i.e., the trajectories of nodes can be anywhere in the network. The model of node mobility falls into the general category of random trip mobility model [11], where nodes' movement can be described by a continuous-time stochastic process and the movement of nodes can be divided into a chain of trips.

Communication between two nodes is allowed only when the distance between them is less than or equal to R and can be performed reliably. Communication zone of a given node consisting of the circle of radius R satisfies the minimum SINR (signal to interference plus noise ratio) requirement with certain outage probability in the wireless fading environment.

A typical communication session between two nodes involves several control and data packet transmissions. Depending on the protocol, nodes may be required to transmit beacons to their neighbors to synchronize their clocks for a variety of reasons (e.g., power management, frequency hopping). Nodes can find out about each other's presence by means of such beacons, or by the reception of other types of signaling packets (e.g., HELLO messages). Once a transmitter knows about the existence of a receiver, it can send data packets, which are typically acknowledged one by one, and the MAC protocol attempts to reduce or avoid those cases in which more than one transmitter sends data packets around a given receiver, which typically causes the loss of all such packets at the receiver. To simplify our modeling of link lifetime, we assume that the proper mechanisms are in place for neighboring nodes to find each other, and that all transmissions of data packets are successful, as long as they do not last beyond the lifetime of the wireless link between transmitter and receiver. Relaxing this simplifying assumption is the subject of future work, as it involves the modeling of explicit medium access control schemes (e.g., [1]).

3 Link lifetime

A bidirectional link exists between two nodes if they are within communication range of each other. In this paper, we do not consider unidirectional links, given that the vast majority of channel access and routing protocols use only bidirectional links for their operation. Hence, we will refer to bidirectional links simply as links for the rest of this paper.

The wireless link between nodes m_a and m_b is broken when the distance between nodes m_a and m_b is greater than R. When a data packet starts at time t_1, the positions of node m_b could be anywhere inside the communication circle defined by the transmission range of m_a and is assumed as uniformly distributed.[1]

Let B (bits/s) be the transmission rate of a data packet, L_p be the length of the data packet, and $t_1 + T_L$ denote the moment that node m_b is moving out of the communication circle. A data packet can be successfully transferred only if nodes m_a and m_b stay within their communication range during the whole communication session of the data packet, that is,

$$L_p/B \le T_L \tag{1}$$

where T_L is the link lifetime (LLT) denoting the maximum possible data transfer duration. Statistically, T_L specifies the distribution of residence time that measures the duration of the time, for node m_b, starting from a random point inside the communication circle with equal probability, to continuously stay inside the communication circle before finally moving out of it. Furthermore, its complementary cumulative distribution function (CCDF) is denoted by $F_L(t)$

$$F_L(t) = P(T_L \ge t) \tag{2}$$

The link outage probability P_{L_p} associated with a particular packet length L_p can be evaluated as

$$P_{L_p} = P\left(T_L < \frac{L_p}{B}\right) = 1 - F_L\left(\frac{L_p}{B}\right) \tag{3}$$

3.1 Distribution of relative velocity

Figure 1 shows the transmission zone of a node (node m_a) which is a circle of radius R centered at the node. The figure shows another node (say node m_b) starting to communicate data with node m_a at time t_2. As shown in the left side of the figure, at time t_2, node m_a is moving at speed v_a with direction θ_a, while node m_b moves at speed v_b with direction θ_b.

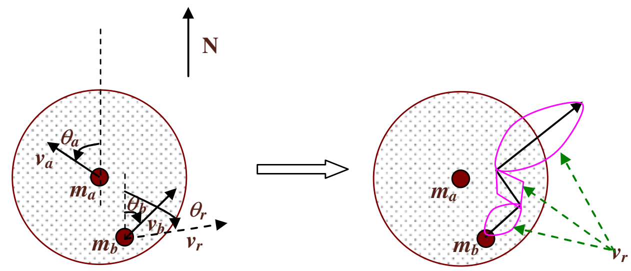

Fig. 1 Graphical illustration of relative velocity

Alternatively, if we consider node m_a as static, node m_b is moving at their *relative speed* and *direction* v_r and θ_c, respectively. An example of resulting trajectories of node m_b moving at relative velocity is given in the right side of Fig. 1. With the assumption that both θ_a and θ_b are uniformly distributed within $[0,2\pi)$, it can be concluded that the composite direction $\theta_c = \theta_b - \theta_a$ is also uniformly distributed within $[0,2\pi)$. In this case, the relative speed v_r can be expressed as

$$v_r = \sqrt{v_a^2 + v_b^2 - 2v_a v_b \cos\theta_c} \tag{4}$$

Conditioning on v_a and v_b and noting the symmetric property of θ_c, the distribution of v_r can be computed as

$$p(v_r) = E_{\{v_a,v_b\}}(p(v_r|v_a,v_b)) \tag{5}$$

$$\begin{aligned} p(v_r|v_a,v_b) &= p(\theta_c)\left|\frac{d\theta_c}{dv_r}\right| \\ &= \frac{1}{\pi}\left|\frac{d}{dv_r}\left(\arccos\left(\frac{v_a^2+v_b^2-v_r^2}{2v_a v_b}\right)\right)\right| \\ &= \begin{cases} g(v_r,v_a,v_b), & |v_a - v_b| \le v_r \le v_a + v_b \\ 0, & \text{otherwise} \end{cases} \end{aligned} \tag{6}$$

where $g(x,y,z) = \frac{2}{\pi}\frac{x}{\sqrt{2(x^2y^2+x^2z^2+y^2z^2)-x^4-y^4-z^4}}$.

In particular, if both nodes move at the same speed $v = v_a = v_b$, we will have

$$p(v_r|v) = \begin{cases} \frac{2}{\pi}\frac{1}{\sqrt{4v^2-v_r^2}}, & v_r \in [0,2v] \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

3.2 Distribution of link lifetime (LLT)

The essence of modeling link dynamics in MANETs consists of evaluating the distribution of LLT, because it reflects the link dynamics resulting from the motions of nodes. LLT measures the duration of time for a node to continuously stay inside the communication range of another node. In our model, this range is a circle.

[1] In mobile ad hoc network, the traffic is generated randomly and nodes are moving randomly. When a node initiate traffic to other nodes, the target node could be anywhere in the network and the realys could also be anywhere in the communication range. Therefore, a uniform distribution assumption naturally fits into the scenario.

Clearly, different mobility models and parameters lead to different LLT distributions, and the main challenge in modeling LLT consists of making the problem tractable and relevant. We know that the relative movement of nodes consists of a sequence of mobility trips, derived from the chain of mobility trips of the two communicating nodes. Let A_s be the starting point of the current mobility trip and the end point of the current trip be denoted by A_d. We have that A_d may be anywhere in the cell, i.e., inside or out of the communication circle. In the case that A_d is located inside the communication circle, it serves as the starting point (i.e., a new A_s) for the next trip and the whole process is repeated. In the evaluation of LLT, this process is repeated until the final A_d is outside of the communication circle.

As illustrated in Fig. 2, the procedure for evaluating the LLT can be modeled as a two-state Markovian process. The residence state $\mathbf{S_0}$ represents the scenario where the end point A_d of the current trip is located inside the communication circle, while the departing state $\mathbf{S_1}$ refers to the complementary scenario in which A_d is outside of communication circle. Compared to the model by Samar and Wicker [5, 6], in which only the last scenario (i.e., state $\mathbf{S_1}$) is considered, the two-state Markovian model reflects the motion of nodes more accurately, which leads to better results in evaluating link dynamics.

Let P_s be the *residence probability*, which denotes the probability that A_d is located inside the communication circle. The probability distribution function (PDF) $S_0(t)$ specifies the distribution of sojourn time of mobility epochs when a node stays in state $\mathbf{S_0}$. Correspondingly, the PDF $S_1(t)$ is used to measure the distribution of the departing time, when node moves out of communication circle and switches to state $\mathbf{S_1}$.

Before eventually moving out of the communication circle (i.e., being switched to the departing state $\mathbf{S_1}$), nodes may stay at the residence state $\mathbf{S_0}$ multiple times. Let N_i be the integer variable counting the number of times for a node to remain in state $\mathbf{S_0}$, and let $\{s_{0,0}, \ldots, s_{0,N_{i-1}}\}$ be the associated random variables that specify the duration of time of trips for each return.

Clearly, $\{s_{0,0}, \ldots, s_{0,N_{i-1}}\}$ are random variables of the same distribution but correlated. However, to make our problem more tractable, we assume that $\{s_{0,0}, \ldots, s_{0,N_{i-1}}\}$ are statistically i.i.d random variables of distribution $S_0(t)$. Our simplifying assumption makes the final result slightly deviated from the real situation when the residence probability becomes larger. However, as we will see later, our model still provides a good approximation, even with a large residence probability.

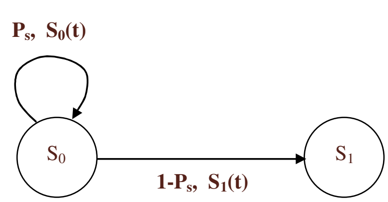

Fig. 2 Two-state Markovian model for LLT evaluation

We define s_1 as the random variable measuring the departing time of distribution $S_1(t)$. The conditional link life time $T_L(N_i)$ and $P(N_i = K)$ can be evaluated as follows:

$$T_L(N_i) = \sum_{i=0}^{N_i-1} s_{0,i} + s_1, \tag{8}$$

$$P(N_i = K) = P_s^K. \tag{9}$$

The characteristic function $U_{T_L}(\theta)$ for the LLT T_L can then be evaluated as

$$\begin{aligned} U_{T_L}(\theta) &= E(e^{j\theta T_L}) \\ &= \sum_{k=0}^{\infty} E(e^{j\theta(\sum_{i=0}^{k-1} s_{0,i}+s_1)}) P(N_i = k) \\ &= \sum_{k=0}^{\infty} U_1(\theta) U_0(\theta)^k P_s^k \\ &= \frac{U_1(\theta)}{1 - U_0(\theta) P_s}, \end{aligned} \tag{10}$$

where $U_0(\theta)$ and $U_1(\theta)$ are the characteristic functions of $S_0(t)$ and $S_1(t)$, respectively.

When the communication circle is small with respect to the network size and nodes' speed, A_d is mostly located outside of the communication circle. Consequently, we have $P_s \ll 1$. Given that $U_0(\theta)$ is the characteristic function of $S_0(t)$, it follows that $|U_0(\theta)| \leq 1$. Finally, it is clear that $U_0(\theta) P_s \ll 1$. Therefore, Eq. 10 can be approximated as

$$U_{T_L}(\theta) \approx U_1(\theta) \tag{11}$$

For clarity, we call Eq. 10 Exact LLT (ES-LLT), which is based on the two-state Markovian model. The approximation in Eq. 11 is called Approximated LLT (AS-LLT), and it reflects the scenario considered by Samar and Wicker [5, 6]. As we will see later, for the random direction mobility model (RDMM), the analytical expression of AS-LLT is the same as the expression in [5, 6], except for a normalization factor.

3.3 Practical implications

It is clear that the two-phase Markov model is a general model that can be applied to networks with different mobility models by adapting its two building blocks $S_0(t)$ and $S_1(t)$ to the specific network and mobility models, including but not restricted to the random trip mobility model.

However, in some practical scenarios, the analytical formulations of $S_0(t)$ and $S_1(t)$ might not be available. Under such circumstances, one can collect a trace data to obtain $S_0(t)$ and $S_1(t)$ and still give an accurate estimate of the overall link lifetime. By doing so, it can greatly reduce the amount of empirical data necessary to accurately estimate link lifetime. Furthermore, one can also obtain analytical formulations by curve-fitting empirical data and incorporate these formulations to our Markov model for an analytical study of the mobility characteristics.

3.4 Link lifetime in random direction mobility model

The random direction mobility model (RDMM) is an important mobility model for MANETs. It improves random waypoint mobility (RWP) model on the stationary uniform nodal distribution, and has been widely adopted [12–16]. However, the analysis on the characteristic of link lifetime of RDMM is quite limited. In this section, we provide a deeper understanding of RDMM by providing an analytical expression for characterizing its link lifetime.

In RDMM, node movements are independently and identically distributed (iid) and can be described by a continuous-time stochastic process. The continuous movement of nodes is divided into mobility epochs during which a node moves at constant velocity, i.e., fixed speed and direction. But the speed and direction varies from epoch to epoch. The time duration of epochs is denoted by a random variable τ, assumed to be exponentially distributed with parameter λ_m. Its CCDF $F_m(\tau)$ can be written as [14]

$$F_m(\tau) = \exp(-\lambda_m \tau). \tag{12}$$

The direction during each epoch is assumed to be uniformly distributed over $[0,2\pi)$ and the speed of each epoch is uniformly distributed over $[v_{\min}, v_{\max}]$, where $v_{\min}$ and $v_{\max}$ denote the minimum and the maximum speed of nodes, respectively. Speed, direction and epoch time are mutually uncorrelated and independent over epochs, and the location and direction of nodes is uniformly distributed [17].

To evaluate the LLT T_L, we need to evaluate P_s, $S_0(t)$, and $S_1(t)$. Let z_d denote the least distance to be traveled by node to move out of the communication circle, starting from the position A_s and without changing the direction and speed v_r. A graphical illustration of z_d is presented in Fig. 3. The probability P_s can now be evaluated through z_d as

$$P_s = E_{z_d}(P_s(z_d)) = \int_{z_d} P_s(z_d)p(z_d)\mathrm{d}z_d \tag{13}$$

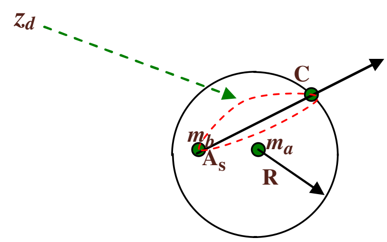

Fig. 3 Graphical illustration of z_d

$$\begin{aligned} P_s(z_d) &= \int_{v_r} P\left(\tau \le \frac{z_d}{v_r}\right)p(v_r)\mathrm{d}v_r \\ &= \int_{v_r} \left(1 - F_m\left(\frac{z_d}{v_r}\right)\right)p(v_r)\mathrm{d}v_r \\ &= \int_{v_r} (1 - \exp(-2\lambda_m z_d/v_r))p(v_r)\mathrm{d}v_r, \end{aligned} \tag{14}$$

where $P_s(z_d)$ is the conditional probability of P_s on z_d, and $p(z_d)$ is the PDF of z_d. The evaluation of z_d directly follows from [18]:

$$p(z_d) = \begin{cases} \frac{2}{\pi R^2}\sqrt{R^2 - \left(\frac{z_d}{2}\right)^2}, & \text{for } 0 \le z_d \le 2R \\ 0, & \text{elsewhere} \end{cases} \tag{15}$$

$S_0(t)$ is the PDF of the time duration for nodes to return to state $\mathbf{S_0}$. Conditioning on z_d and assuming that the starting time is at time 0, $S(t)$ is the probability of node m_b changing its relative velocity at time t on condition that A_d is located inside the communication circle. Therefore,

$$S_0(t) = E_{z_d}(S_0(t|z_d)) \tag{16}$$

$$\begin{aligned} S_0(t|z_d) &= \frac{1}{P_s}P(t = \tau, z_d \ge v_r\tau|z_d) \\ &= \frac{1}{P_s}P(\tau = t)P\left(v_r \le \frac{z_d}{t}\middle|z_d\right) \\ &= \frac{1}{P_s}2\lambda_m \mathrm{e}^{-2\lambda_m t}\int_0^{\min\{V_m, \frac{z_d}{t}\}} p(v_r)\mathrm{d}v_r, \end{aligned} \tag{17}$$

where $S_0(t|z_d)$is the conditional PDF on z_d and V_m is the maximum speed of v_r.

$S_1(t)$ can be evaluated in much the same way as we have done for $S_0(t)$. Conditioning on z_d and assuming that the starting time is at time 0, $S_1(t)$ is simply the probability of the node m_b moving out of the communication circle at time t with relative velocity being kept constant. Similar to the previous case, we have

$$S_1(t) = E_{z_d}(S_1(t|z_d)) \tag{18}$$

$$S_1(t|z_d) = \frac{1}{1-P_s} P\left(t = \frac{z_d}{v_r}, z_d \le v_r \tau | z_d\right)$$
$$= \frac{1}{1-P_s} P(\tau \ge t) p\left(v_r = \frac{z_d}{t}\right) \left| \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{z_d}{t}\right)\right|$$
$$= \frac{1}{1-P_s} \exp(-2\lambda_m t) p_{v_r}\left(\frac{z_d}{t}\right) \frac{z_d}{t^2}, \qquad (19)$$

where $S_1(t|z_d)$ is the conditional PDF on z_d using the Jacobian of the transformation.

Let us define v_{s_1} to be the conditional relative velocity associated with state $\mathbf{S_1}$ such that $p(v_{s_1}) = p(v_r|S_1)$ and it should be noted that the distribution of v_{s_1} can be greatly different from the distribution of $p(v_r)$. Accordingly, an alterative way to evaluate $S_1(t)$ is:

$$S_1(t) = E_{v_{s_1}}(S_1(t|v_{s_1})) \qquad (20)$$

$$S_1(t|v_{s_1}) = \frac{1}{1-P_s} P\left(t = \frac{z_d}{v_{s_1}} \middle| z_d \le v_{s_1}\tau\right)$$
$$= \frac{1}{1-P_s} P(\tau \ge t) p(z_d = v_{s_1} t) \frac{\mathrm{d}}{\mathrm{d}t}(v_{s_1} t)$$
$$= \begin{cases} \frac{4e^{-2\lambda \mathrm{mt}}}{\pi(1-P_s)} \frac{v_{s_1}}{2R} \sqrt{1 - (\frac{v_{s_1} t}{2R})^2}, & 0 \le t \le \frac{2R}{v_{s_1}} \\ 0, & \text{elsewhere} \end{cases}$$

where $S_1(t|v_{s_1})$ is the conditional PDF of $S_1(t)$ on v_{s_1}. A detailed examination of Eq. 20 reveals that it shares the same core analytical expression of link lifetime distribution of Eq. 15 in [6], with the only exception that a normalization factor $e^{-2\lambda_m t}/(1-P_s)$ accounts for the probability of nodes leaving for state $\mathbf{S_1}$. It implies that AS-LLT formula, solely relying on $S_1(t)$, gives the same link lifetime distribution as in [6].

4 Path lifetime in MANETs

We have examined the dynamics of link lifetime for a point-to-point link. However, for most cases in MANETs, a packet needs to be forwarded by several intermediate nodes before finally reaching the destination. The source node, intermediate nodes and destination node collectively form a multi-hop path for the packet. Clearly, path dynamics is also an essential metric for protocol design and optimization. Han et al. showed [19, 20] that path dynamics converge asymptotically to an exponential distribution, when links are assumed to be independent or of limited dependence. The result works well when a path involves a significant number of hops but not for paths with a small to moderate number of hops. In this section, we will extend the proposed analytical framework to evaluate path dynamics with small to moderate numbers of hops, assuming that each link along the path behaves independently of others. In reality, adjacent links have some correlation, which is difficult to model. Modeling dependent links requires a number of conditional probability distributions, and a solution may not be feasible. The independence assumption that we make greatly simplifies the analysis and still provides a good approximation.

As illustrated in Fig. 4, a packet from source node M_1 needs to follow the ordered set of links $\{T_1 \to T_2 \to \cdots \to T_{K-1}\}$ to reach the destination node M_K. Successful delivery of the packet requires that none of these links on the path breaks during packet transmission. When any of the links breaks, the path no longer exists and the path discovery process needs to be reinitiated to find alternative paths. In other words, lifetime $T_P(K)$ of the $(K-1)$-hop path is the minimum lifetime of the links that form it, and can be written as

$$T_P(K) = \min\{T_1, \ldots, T_{K-1}\} \qquad (21)$$

Because links are assumed to operate independently with i.i.d motion, their lifetime also follows the same statistical distribution as T_L. However, when the source node initiates a data transfer to the destination node, links may have been in existence for some time; therefore, as Fig. 4 illustrates, the lifetime T_i, $i \in \{1,\ldots,K-1\}$ of the directional link on the data path should be the *residual lifetime* of the link, i.e.,

$$T_i = T_L(\epsilon_i), \quad i \in \{1, \ldots, K-1\} \qquad (22)$$

where $\varepsilon_i \ge 0$ is a random variable representing the elapsed time of the link $M_i \to M_{i+1}$ before the data path started and clearly, $T_L = T_L(0)$.

From Sect. 3, we know that the evaluation of $T_L(\varepsilon_i)$ depends on a set of three parameters, i.e., the spatial distribution of nodes at time ε_i, the distribution of speed $v_r(\varepsilon_i)$ at time ε_i, and the residual change time distribution $\tau(\varepsilon_i)$ at ε_i. At time 0 and ε_i, nodes are expected to follow the same stationary distribution and therefore resemble each other. Similarly, it can be expected that the speed distribution of

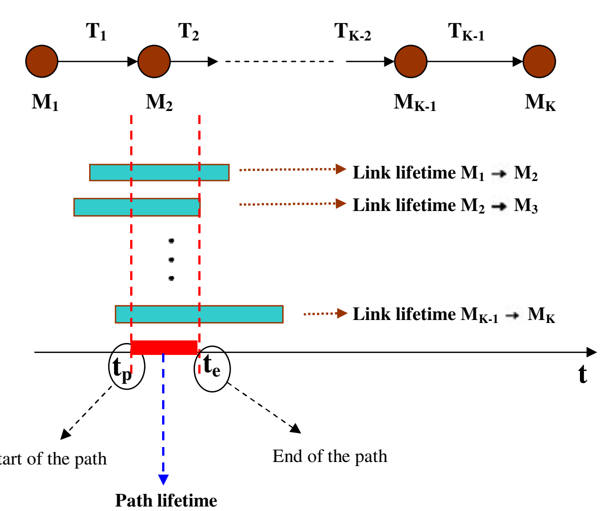

Fig. 4 Path structure

v_r will be also the same. Therefore, we expect that the distribution of $\tau(\varepsilon_i)$ and $\tau(0)$ will resemble each other. In particular, we know that the distribution of $\tau(0)$ for the RDMM model is exponentially distributed. Accordingly, because of the memoryless property of the exponential distribution, the distribution of $\tau(\varepsilon_i)$ and $\tau(0)$ will exactly resemble each other. Finally, we conclude that the distribution of T_i will resemble the distribution of $T_L = T_L(0)$.

Summarizing the above discussion, the CCDF $F_P(K,t)$ of the lifetime for a $(K-1)$-hop path can be computed as

$$F_P(K,t) = F_L^{K-1}(t). \tag{23}$$

5 Model validation

5.1 Simulation setup

In the simulation, there are 100 nodes randomly placed in a 1,000 × 1,000 m square cell. Each node has the same transmit power and two profiles of radio transmission range are chosen for the simulation experiments. Both are within the coverage of IEEE 802.11 PHY layer and they are {200 m,100 m}. After initial placement, nodes keep moving continuously according to the RDMM model. The mobility parameter λ_m is the same as the one in [21] ($\lambda_m = 4$), which means that nodes change their velocity at every ¼ h in average. Furthermore, we assume that every node is moving at the same constant speed and only its direction is changed according to the RDMM model. The simulation with variable speeds can be obtained by averaging the results from every speed with respect to the distribution of speed v. However, it should be noted that the relative speeds between nodes are not constant and their statistics are derived in Sect. 3.1. Three different speeds are simulated $v \in \{1, 10, 20\}$ (m/s), which range from pedestrian speed to vehicle speed. Combining the power profile and velocity profile, six different scenarios are simulated {*I*: (200 m,1 m/s); *II*: (100 m, 1 m/s); *III*: (200 m, 10 m/s); *IV*: (100 m, 10 m/s); *V*: (200 m, 20 m/s); *VI*: (100 m, 20 m/s)}.

Nodes are randomly activated for data transmission. The traffic of activated nodes is supplied from a constant bit rate (CBR) source with a packet rate of 0.5 p/s. Given that the choice of specific MAC layer and routing protocol may affect the results, we assume perfect MAC and routing protocols, rendering zero delays or losses due to their functionalities. This enables the simulation to capture statistics solely due to mobility.

5.2 Accuracy of models

Table 1 describes the residence probability P_s for all six scenarios. As shown in Eqs. 16 and 18, the characteristics of mobility are governed by the ratio between the radius R of the communication circle and the speed v, which we call the relative radius (ReR) $\frac{R}{v}$. Among the six different scenarios, there are five different ReR values {5,10,20,100,200}, given that IV and V scenario have the same ReR and exhibit similar results, as will be seen from simulations. As shown in Table 1, the residence probability increases with ReR, indicating that it is more likely for nodes with larger ReR to stay inside the communication circle.

Table 1 Residence Probability P_s

Radius R (m)	Speed v (m/s)		
	$v = 1$	$v = 10$	$v = 20$
$R = 100$	$P_s = 0.194$	0.033	0.018
$R = 200$	$P_s = 0.3072$	0.058	0.033

Figure 5 presents the results for link lifetime ES-LLT and AS-LLT predicted by our analytical model, as well as by the simulations. The results clearly confirm that the two-state Markovian model is a powerful tool to model link dynamics of the link lifetime distribution as a function of node mobility. It can be also observed that the ES-LLT formula, obtained from the Markovian model, shows a very good match with simulations in all scenarios. On the other hand, the AS-LLT formula, which corresponds to the model by Samar and Wicker [5, 6] gives good approximations to the simulations only for small values of ReR ($\frac{R}{v}$), and greatly deviates from the simulations when ReR becomes large, i.e., larger residence probability P_s and larger possibility for nodes to stay inside communication circle.

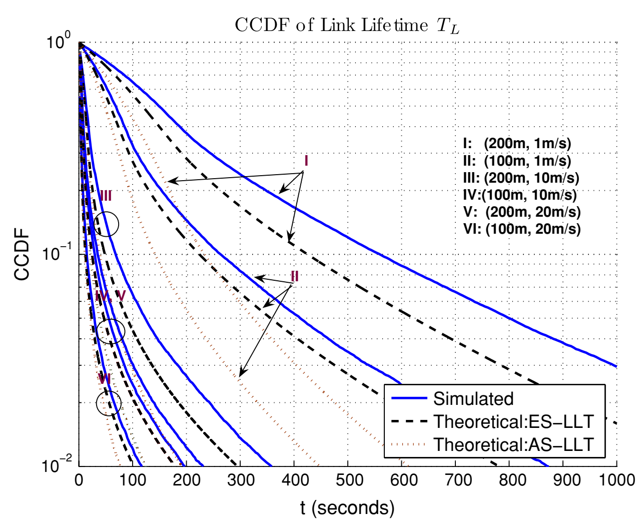

Fig. 5 Link lifetime T_L (RDMM): simulated, ES-LLT(Markovian), and AS-LLT

As stated in Sect. 3.3, in some practical scenarios, the analytical formulations of $S_0(t)$ and $S_1(t)$ might need to be obtained from empirical data to characterize the overall link lifetime. Figure 6 presents such a result, where trace data are generated from the random waypoint (RWP) model. Because there is no analytical formulations of $S_0(t)$ and $S_1(t)$ for RWP, the two-phase Markov model is applied by using empirical simulated data to estimate the link lifetime. The results clearly confirm the accuracy, effectiveness and generality of our Markov model to analyze more practical mobility models.

Figures 7 and 8 present the results of path lifetime. It can be observed that path lifetime can be modeled accurately with the proposed Markovian model, and is only slightly affected by the independence assumption used to derive it.

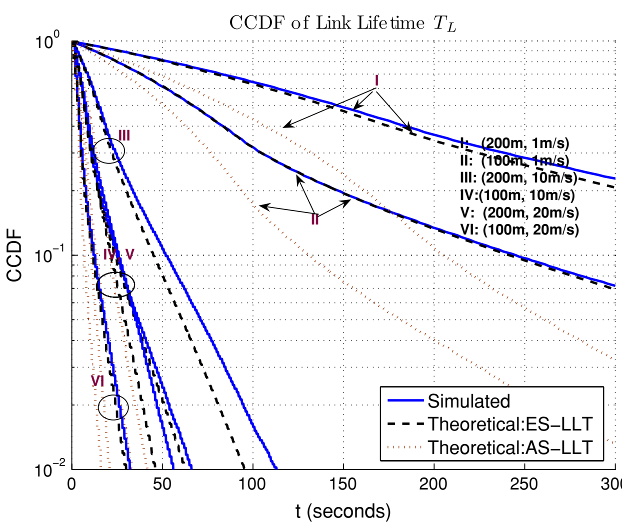

Fig. 6 Link lifetime T_L (RWP): simulated, ES-LLT(Markovian), and AS-LLT

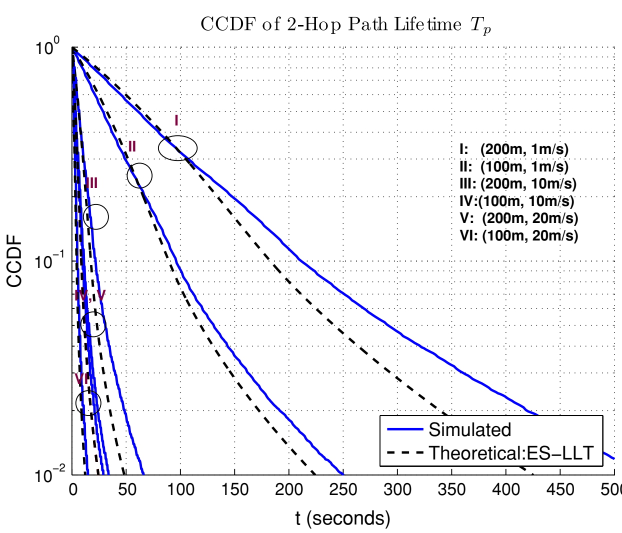

Fig. 7 Simulation: 2-hop path lifetime

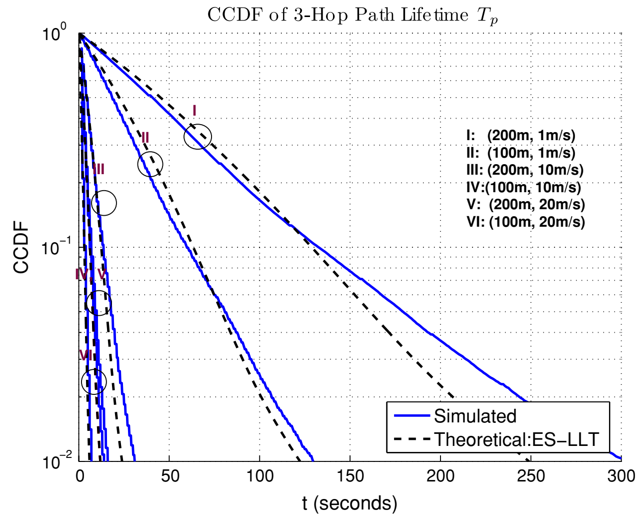

Fig. 8 Simulation: 3-hop path lifetime

In summary, the Markovian model (ES-LLT formula) is more accurate model than the AS-LLT formula [5, 6] for all ranges of ReR and shows good approximations to all simulations, in contrast to the AS-LLT formula that gives good approximation only when ReR is relatively small.

6 Packet-length optimization

6.1 Link lifetime and packet length

Given that nodes move in a MANET, the data transfer can be temporarily broken if any link on the path to the destination is broken. An alternative path may not be available immediately, and significant delay can be incurred in repairing a route. Within the context of MANETs, it is important to use information packet lengths that maximize the end-to-end throughput. If a information data-packet length is too long, frequent link breaks can lead to significant packet dropout during the transfer. On the other hand, if data packet length is too short, the packet-header overhead and channel access overhead can reduce the effective throughput significantly. Hence, a judicious choice of information packet length as a function of link dynamics can be of great importance in maximizing throughput in MANETs. However, this problem has been overlooked in the past, because its solution requires knowledge of statistics of link lifetime. With the computed CCDF in Sect. 3, we are able to provide packetizing schemes optimized on various systematic constraints.

When the length of packets is constant, it is natural to ask what the optimal packet length would be. For every packet length L_p, we know that there is an associated link outage probability P_{L_p} specifying the probability of link breach during packet transfer. Every dropped packet during link outage is either lost or must be retransmitted and therefore reduces the effective throughput. The optimal packet length is chosen such that the total throughput is maximized.

One approach is to simply choose the maximum possible packet length L_0 that satisfies a pre-defined link outage probability requirement. We call this strategy link outage priority design (LOPD) and it can be described as

$$L_0 = \max_{L_p} P_{L_p} \leq \omega_p \tag{24}$$

where ω_p is a constant specifying the link dropout probability requirement.

Alternatively, we can use a cost function $C(L_p, P_{L_p})$ that incorporates the negative effect from the packet retransmission into evaluating the effective throughput $ET(L_p)$ for a specific packet length L_p. The cost function $C(L_p, P_{L_p})$ could be a systematic constraint from upper layer, such as the negative effects from delay and packet retransmissions. Further optimizing the effective throughput $ET(L_p)$ gives the optimal packet length L_0. Consequently, we refer to this strategy link throughput priority design (LTPD).

In LTPD, when the packet length is L_p, we can describe the effective throughput $ET(L_p)$ function as

$$ET(L_p) = (1 - P_{L_p}) \cdot L_p - C(L_p, P_{L_p}) \cdot P_{L_p} \cdot L_p \tag{25}$$

The optimal packet length L_0 will be the one that maximizes the effective throughput

$$L_0 = \max_{L_p} ET(L_p) \tag{26}$$

Normally, P_{L_p} is a monotonically decreasing function w.r.t. packet length. When the cost function is chosen to be a constant penalty value, i.e., ($C(L_p, P_{L\_p}) = C$) by taking the derivative with respect to L_p, the optimal packet length L_0 is the value satisfying

$$1 - (1 + C)P_{L_0} = (1 + C)L_0 \frac{\mathrm{dP_{L_p}}}{\mathrm{d}L_p}\bigg|_{L_p = L_0} \tag{27}$$

In Fig. 9, we exploit the application of the link lifetime distribution to the optimization of packet-length design using the same examples of the previous section. For illustration purpposes, the cost function for our example of LTPD is chosen as a constant penalty value of 2 (i.e., $C(L_p, P_{L_p}) = 2$). However, it should be noted that the practical cost function can be much more complicated and determined by upper layers for a cross-layer optimization solution. However, computing the optimum choice for $C(L_p, P_{L_p})$ is beyond the scope of this paper. The effective throughput $ET(L_p)$ is computed for every L_p and drawn for all three methods: Simulated, ES-LLT (Markovian model) and AS-LLT. As expected, ES-LLT approximates the simulation very well, while AS-LLT tends to

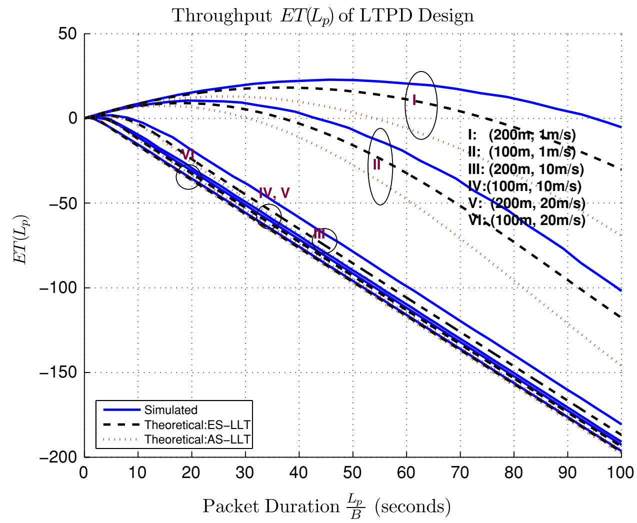

Fig. 9 LTPD design

conservatively underestimate the effective throughput for larger ReR. In addition, all curves of the effective throughput (either Simulated, ES-LLT or AS-LLT formula) are convex functions with numerical solutions readily available.

The optimized solutions $\frac{L_0}{B}$ on packet design for all design methods are illustrated in Fig. 10. In the simulation, the link outage tolerance of LOPD is set to be $\omega_p = 0.1$, i.e., the maximum link outage probability should be less than 10%. Two key observations should be made: First, the ES-LLT (Markovian model) approaches the simulated optimal solution well for LTPD and LOPD, and signifies substantial improvement of throughput over the AS-LLT model [5, 6]. Second, LTPD suggests a balanced design between longer packet and larger retransmission rate to offer higher throughput over LOPD. On the other hand, LOPD tends to be more conservative on throughput but renders fewer packet retransmissions.

Another important observation from Fig. 10 is that the optimal solutions, obtained from either the simulation or Markovian ES-LLT formula, exhibit linear proportion to the ReR value $\frac{R}{v}$. It suggests that mathematically, the optimal packet design should follow the rule[2]

$$\frac{L_0}{B} = \Theta\left(\frac{R}{v}\right) \tag{28}$$

6.2 Path lifetime and packet length

We can also investigate the optimal packet length for a given path and the effect of hop count on the optimal

[2] We recall that $f(n) = \Theta(g(n))$ means there exist positive constants c_1,c_2 and M, such that $0 \leq c_1 g(n) \leq f(n) \leq c_2 g(n) \forall n > M$.

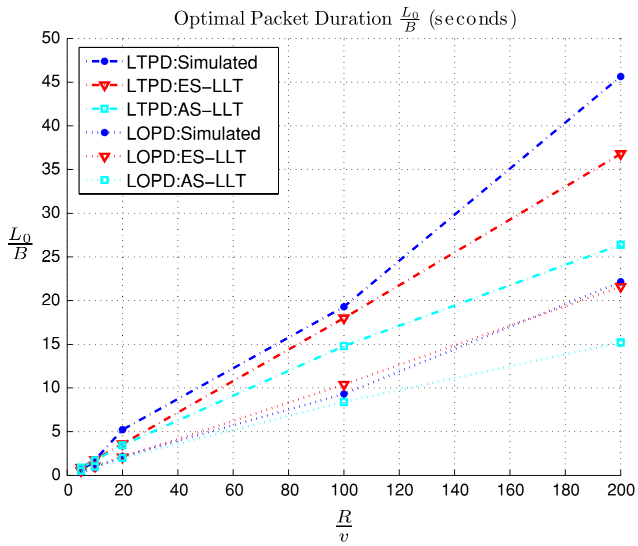

Fig. 10 Optimal packet duration $\frac{L_0}{B}$

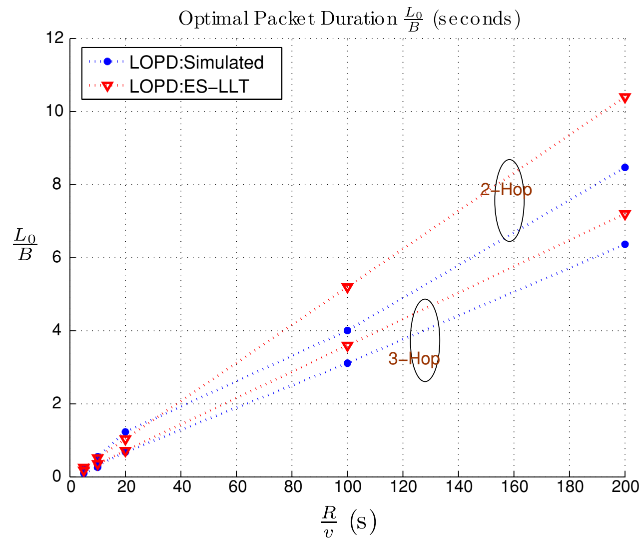

Fig. 11 Optimal packet length for multi-hop paths

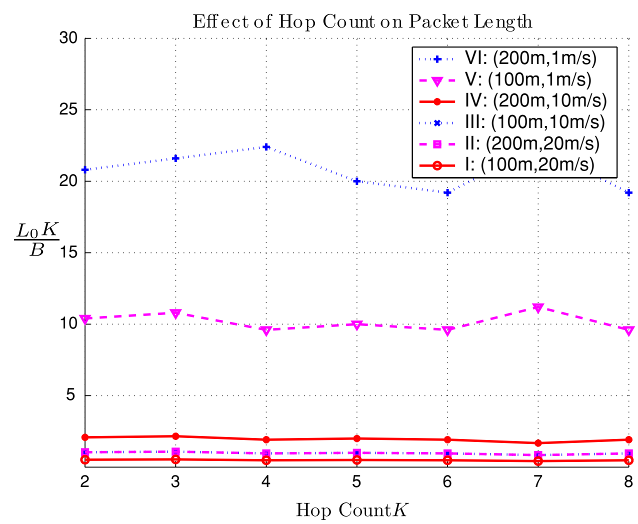

Fig. 12 Effect of hop count on packet length

packet length. Extending the optimal packet design example in Sect. 6 for a 2-hop path, the results we obtain are shown below.

In Fig. 11, we only present the results following LOPD, because the penalty of a path breakage is usually pretty high and a more practical design is to ensure that packet can get through the path with low outage probability. For example, in AODV [22], the source needs to flood the network to reinitiate a route to the destination, when an existing path breaks. Furthermore, similar to the case of link lifetime, the linear relationship between the optimal packet length and network parameters can also be observed. Although only the results for 2-hop and 3-hop paths are shown here, we have examined cases with different hop counts (various K) and they all exhibit similar behavior.

Another aspect examined here is the effect of hop count on the choice of optimal packet length. In Fig. 12, for each K-hop path, the optimal packet length is chosen based on LOPD design criterion. We can see that the packet length should also be chosen such that[3]

$$\frac{L_0 K}{B} = \Theta(1). \tag{29}$$

Combining our observations from Figs. 11 and 12, we conclude that the packet length for a K-hop path should be designed as

$$\frac{L_0}{B} = \Theta\left(\frac{R}{vK}\right). \tag{30}$$

7 Cache lifetime optimization

From the previous analysis, we observe that the optimal packet length should be chosen based on the knowledge of hop distance between source and destination. Similarly, the route caching scheme of on-demand routing protocols should follow the same rule. However, without knowing the relationship represented in Eq. 30, it is difficult to determine the timeout value for different routes. As a result, on-demand protocols like DSR [23] use the same value for the parameter *RouteCacheTimeout* to set the timeout *for all* cached routes. However, based in Eq. 30, we know that the cache timeout

[3] Equivalently, we can transfer K to the other side of this equation. It means that when the number of hops increases for a constant bandwidth B, the packet length should decrease.

scheme for DSR and any on-demand routing protocol should be adapted to the hop count of the cached routes. An example of a mobility-adaptive cache timeout scheme for DSR derived based on the analytical guidance that we gain from our model is the following:

- A base parameter *RouteCacheTimeout* takes user input to set timeout value for a point to point link (one-hop path). Such value can be either chosen in ad hoc manner or determined from LTPD or LOPD design of Sect. 6.
- The timeout value T_k of a route is determined based on the base parameter and the number (K) of links involved on the route. And it can be expressed as $T_k = RouteCacheTimeout/K$.

Figure 13 presents results of this illustrative hop-adaptive caching strategy for DSR. In the simulation, 50 nodes are randomly moving in a 1500 × 500 m area according to the random waypoint model without pause. The minimum speed is zero and the maximum speed V varies. The source and destination pairs are randomly chosen. Ten pairs are simulated and traffics are supplied from CBR source at a rate 4 p/s. Each packet is of size 64 bytes and all simulations run for 900 s. Ten random seeds are simulated for each configuration. The implementation of DSR used for comparison is the default implementation in *Qualnet 3.9.5*.

Figure 13 compares the default DSR (DSR-Default) and the hop-adaptive DSR (DSR-ADA). It can be observed that, by effectively timing out stale paths, DSR-ADA reduces the overhead incurred from route error (RERR) packets and improves the overall packet delivery ratio. This further confirms that our modeling framework can be used to improve existing routing protocols. However, it should be noted that the above DSR-ADA cache strategy is by no means a perfect solution to the caching problem in on-demand routing. It is meant simply as an example to illustrate the effectiveness of analytical results that are derived in this paper.

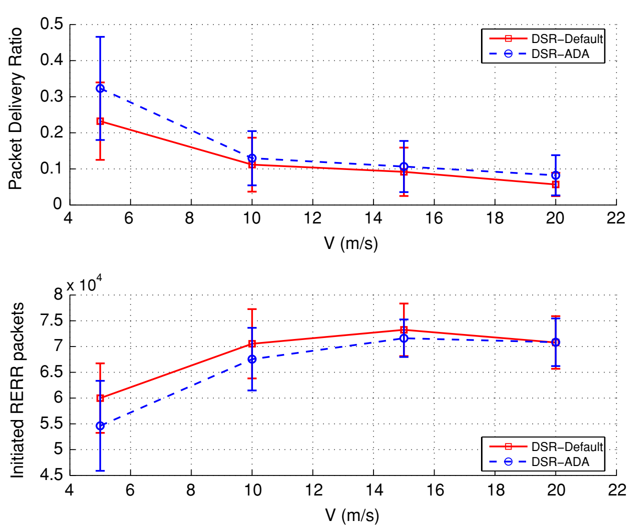

Fig. 13 Illustrative example of cache guideline

8 Analysis of throughput, average delay, and storage

We consider the well-known two-hop forwarding scheme introduced by Grossglauser and Tse [8, 9] in the computation of the throughput of a MANET. Following a bottom-up approach and utilizing our analytical results on the optimal packet length in Sect. 6, we rediscover exactly the same result on the throughput, showing the effectiveness of our models on the computation of throughput and capability to handling more complex schemes. Furthermore, we give a comprehensive packet-level and bit-level analysis on the delay and storage requirement, in contrast to most studies where only the packet level analysis can be conducted.

8.1 Throughput

Because the two-hop forwarding scheme is such that packets are transferred only when nodes are close to each other, the packet length L_0 should be chosen according to the results from the analysis of link lifetime, i.e., $L_0 = \Theta\left(\frac{R \cdot B}{E(v)}\right)$. Based on the mobility models in [21], we have one data packet transferred on average for every time duration of $I = \Theta\left(\frac{L^2}{E(v) \cdot R}\right)$. Accordingly, the link throughput T_0 for one pair of nodes can be computed as

$$T_0 = \frac{L_0}{I} = \Theta\left(\frac{R^2 B}{L^2}\right) \tag{31}$$

Meanwhile, R should be chosen on the order of $\Theta(L/\sqrt{n})$, i.e., $\frac{R}{L} = \Theta\left(\frac{1}{\sqrt{n}}\right)$ [8, 9]. Therefore, the above equation is reduced to $T_0 = \Theta(B/n) = \Theta(1/n)$. For each source node, except for the direct path, we can have at most $n - 2$ such 2-hop paths to help deliver its packet to destination. Therefore, the per source-destination throughput can be computed as

$$\Lambda(n) \leq T_0 \cdot (n-2) \Rightarrow \Lambda(n) = \Theta(1). \tag{32}$$

Thus far, we have obtained exactly the same results in [8, 9] on throughput, and the above analysis leads to the following conclusion on the throughput $\Lambda(n)$ of a MANET subjecting to the two-hop forwarding discipline.

Theorem 1 *For MANETs with unrestricted mobility, we have* $\Lambda(n) = \Theta(1)$ *for generic mobility models.*

8.2 Delay & storage

To compute the delay and storage incurred in a MANET, we assume that every relay node maintains a separate queue for each S-D pair and the queue is served in a First-Come-First-Serve (FCFS) manner. Because all cells

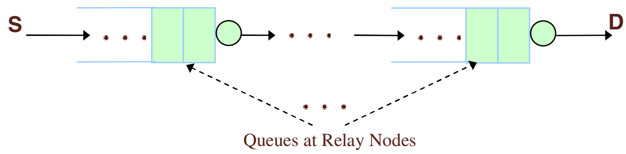

Fig. 14 Tandem queue

resemble each other and nodes have iid movements, it is clear that all such queues are similar.

Consider an S-D queue at relay node m_r, a packet arrives when node m_r and the previous relay node (or the source node) simultaneously come into the communication region; a packet departs when m_r meets another relay node (or the destination node) in the communication region. Both the inter-arrival time and the inter-departure time are of the same order as link interarrival time (LIT) from the mobility models in [21]. We also know from [21] that LIT can be characterized as exponentially distributed, each queue is then characterized of a Poisson arrival process with exponential service time, thus being an M/M/1-FCFS queue.

For each S-D pair, queues at relay nodes construct a M/M/1-FCFS feedforward tandem network[4] as in Fig. 14. An important property of a M/M/1-FCFS feedforward tandem network is the *Jackson's theorem* (see [24], page 150), i.e., if the tandem network with exponential service time is driven by a Poisson arrival process, every queue in the tandem network behaves as if it were an independent M/M/1-FCFS queue and thus can be analyzed individually. Recall the following properties for a M/M/1-FCFS queue (see [24], chapter 3) in the following lemma.

Lemma 1 *Consider a discrete M/M/1-FCFS queue. Let* $1-\varepsilon$ *be the traffic intensity and* λ *be the exponential service rate of the queue, the average delay is given by*

$$E(D) = \frac{1}{\lambda\epsilon} = \Theta\left(\frac{1}{\lambda}\right) \tag{33}$$

Furthermore, the mean and variance of the occupancy of the queue N_q *is*

$$E(N_q) = \frac{1-\epsilon}{\epsilon} = \Theta(1) \tag{34}$$

$$Var(N_q) = \frac{1-\epsilon}{\epsilon^2} = \Theta(1) \tag{35}$$

Recall that the service rate of each queue can be written as $\lambda = \Theta\left(\frac{E(v)R}{L^2}\right)$ [21] and also that the delay for each S-D pair is the summation of delays occurred at relay nodes. Assuming that every relay node carries traffic for $\Theta(n)$ S-D pairs, we can now summarize the network performance in terms of average delay and storage in the following theorem.

Theorem 2 *The average packet delay in MANETs with unrestricted mobility is given by*

$$D(n) = \Theta\left(\frac{L^2}{E(v)R}\right) \tag{36}$$

and the average information bit delay $D_b(n)$ *is*

$$D_b(n) = \frac{D(n)}{L_0} = \Theta\left(\frac{L^2}{R^2B}\right) \tag{37}$$

Furthermore, the mean and variance of the packet occupancy (i.e., storage requirement) is given by

$$E(N_p) = Var(N_p) = \Theta(n) \tag{38}$$

and the corresponding bit storage requirement N_b *is*

$$E(N_b) = Var(N_b) = \Theta(n)\cdot\Theta\left(\frac{RB}{E(v)}\right) \tag{39}$$

Summarizing, we can make the following observations:

- Throughput of the network scales as $\Lambda(n) = \Theta(1)$ and packet-wise storage scales as $\Theta(n)$. Attaining optimal throughput comes with the price of increase in storage.
- Mobility can help alleviate packet delay but it does not help the bit-wise delay. It might be counter intuitive on a first glance. However, a detailed examination reveals that faster mobility brings more opportunities for nodes to deliver information packets but at the cost of reduced time for each communication. When information packets are optimally chosen, the negative effect from reduced communication time balances off the benefit from faster mobility. Eventually, the only way to reduce the bit-wise delay is to increase the bandwidth and data rate for transmission, or use more transmission power to increase the communication range.

9 Conclusions

We have presented an analytical framework for the characterization of link and path lifetimes in MANETs with unrestricted mobility. Given the existence of prior attempts to incorporate link dynamics in the modeling of routing and clustering schemes [4, 25, 26], we believe that this new framework will find widespread use by researchers interested in the analytical modeling and optimization of MAC and routing protocols in MANETs. The advantage of our framework is that it accurately describes link and path dynamics as a function of node mobility.

We illustrated how our framework can be applied by using it to address the optimization of packet lengths and

[4] For delay to be finite, the arrival rate must be strictly less than the service rate but in this case, symmetric movements lead to a fully loaded tandem queue. To avoid this, we assume that if the available throughput is $\Lambda(n)$, each source generates traffic at a rate $(1-\epsilon)\Lambda(n)$, for some $\varepsilon > 0$.

the design of route caching strategies as a function of link and path dynamics in MANETs. The optimized solutions obtained from the proposed analytical framework show a substantial improvement on network throughput and protocol performance. Furthermore, a performance analysis of throughput, delay and storage is also presented for MANETs using the two-hop forwarding scheme proposed by Grossglauser & Tse [8, 9] to give deeper insights to the understanding of system tradeoffs.

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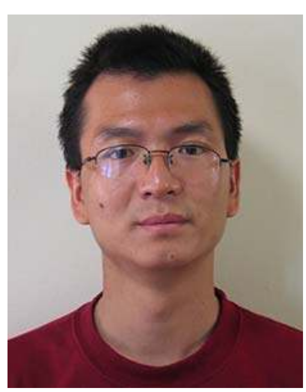
Author Biographies



Xianren Wu received the B.S. degree in Communication Engineering from Nanjing University of Posts and Telecommunications, Nanjing, China, in 1998 and the M.S. degree in Information Engineering from Beijing University of Posts and Telecommunications, Beijing, China, in 2001. He is currently a Ph.D. candidate at University of California at Santa Cruz, with research topic on analytical modeling and performance analysis of mobile ad hoc networks. And he received best paper award in SPECTS 2007 conference. His general research interest spans over mobile ad hoc networks, wireless communications and coding theory.

Hamid R. Sadjadpour received his B.S. and M.S. degrees from Sharif University of Technology with high honor and Ph.D. degree from University of Southern California in 1986, 1988, and 1996 respectively. After graduation, he joined AT&T as a member of technical staff, later senior technical staff member, and finally Principal member of technical staff at AT&T Lab. in Florham Park, NJ until 2001. In fall 2001, he joined University of California, Santa Cruz (UCSC) where he is now an Associate professor. He has served as technical program committee member in numerous conferences and as chair of communication theory symposium at WirelessCom 2005, and chair of communication and information theory symposium at IWCMC 2006, 2007, and 2008 conferences. He has been also Guest editor of EURASIP on special issue on Multicarrier Communications and Signal Processing in 2003 and special issue on Mobile Ad Hoc Networks in 2006, and is currently Associate editor for Journal of Communications and Networks (JCN). He has published more than 90 publications. His research interests include space-time signal processing, scaling laws for wireless ad hoc networks, performance analysis of ad hoc and sensor networks, and MAC layer protocols for MANETs. He is the co-recipient of International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS) 2007 best paper award. He holds more than 13 patents, one of them accepted in spectrum management of T1.E1.4 standard.

J. J. Garcia-Luna-Aceves holds the Jack Baskin Chair of Computer Engineering at the University of California, Santa Cruz (UCSC), and is a Principal Scientist at the Palo Alto Research Center (PARC). Prior to joining UCSC in 1993, he was a Center Director at SRI International (SRI) in Menlo Park, California. He has been a Visiting Professor at Sun Laboratories and a Principal of Protocol Design at Nokia. Dr. Garcia-Luna-Aceves has published a book, more than 330 papers, and 24 U.S. patents. He has directed 25 Ph.D. theses and 20 M.S. theses since he joined UCSC in 1993. He has been the General Chair of the IEEE SECON 2005 Conference; Program Co-Chair of ACM MobiHoc 2002 and ACM Mobicom 2000; Chair of the ACM SIG Multimedia; General Chair of ACM Multimedia '93 and ACM SIGCOMM '88; and Program Chair of IEEE MULTIMEDIA '92, ACM SIGCOMM '87, and ACM SIGCOMM '86. He has served in the IEEE Internet Technology Award Committee, the IEEE Richard W. Hamming Medal Committee, and the National Research Council Panel on Digitization and Communications Science of the Army Research Laboratory Technical Assessment Board. He has been on the editorial boards of the IEEE/ACM Transactions on Networking, the Multimedia Systems Journal, and the Journal of High Speed Networks. He is a Fellow of the IEEE and is listed in Marquis Who's Who in America and Who's Who in The World. He is the co-recipient of Best Paper Awards at the SPECTS 2007, IFIP Networking 2007, and IEEE MASS 2005 conferences, and the Best Student Paper Award of the 1998 IEEE International Conference on Systems, Man, and Cybernetics. He received the SRI International Exceptional-Achievement Award in 1985 for his work on multimedia communication and in 1989 for his work on routing algorithms.